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Hierarchical Statistical 3D "Atomistic' Simulation of Decanano MOSFETs: Drift-Diffusion, Hydrodynamic and Quantum Mechanical Approaches

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When MOSFETs are scaled to deep submicron dimensions the discreteness and randomness of the dopant charges in the channel region introduces significant fluctuations in the device characteristics. This effect, predicted 20 year ago [1], has been confirmed experimentaly [2] and in simulation studies [3]. The impact of the fluctuations on the functionality, yield, and reliability of the corresponding systems shifts the paradigm of the numerical device simulation. It becomes insufficient to simulate only one device representing one macroscopical design in a continuous charge approximation. An ensemble of macroscopically identical but microscopically different devices has to be characterized by simulation of statistically significant samples. The aims of the numerical simulations shift from predicting the characteristics of a single device with continuous doping towards estimating the mean values and the standard deviations of basic design parameters such as threshold voltage, subthreshold slope, transconductance, drive current, etc. for the whole ensemble of 'atomistically' different devices in the system. It has to be pointed out that even the mean values obtained from 'atomistic' simulations are not identical to the values obtained from continuous doping simulations [4].

Simulations have shown that not only the fluctuation in the average doping density associated with the dopant number fluctuation, but also the individual random distribution of dopants in the channel region have significant contribution to the parameter fluctuations in agresively scaled MOSFETs. This advocates the need for full scale 3D 'atomistic' simulations with fine grain discretization, where the charge associated with each individual dopant is resolved. Thus the statistical 'atomistic' simulations become essentially a four dimensional problem, where the fourth dimension is the size of the statistical sample. The use of 'atomistic' simulations in the practical design of the next generation of MOSFETs along the Silicon Roadmap requires the development of efficient 'atomistic' simulation strategies.

In this paper we present a hierarchical approach to the 'atomistic' simulation of aggressively scaled decanano MOSFETs. A full scale 3D drift-diffusion 'atomostic' simulation approach is first described and used for verification of the more economical, but also more restricted, options. To reduce the processor time and memory requirements at high drain voltage we have developed a self-consistent option based on a thin slab solution of the current continuity equation only in the channel region. This is coupled to the Poisson's equation solution in the whole simulation domain in the Gummel iteration cycles. The accuracy of this approach is investigated in comparison with the full self-consistent solution. At low drain voltage only single solution of the nonlinear Poisson equation is sufficient to extract the current with satisfactory accuracy.

A pilot version of a hydrodynamic 'atomistic' simulator has been developed in order to study the effect of the nonequilibrium, non local transport in decanano MOSFETs on the random dopant induced current fluctuations. For the first time we have also applied the density gradient approach in 3D to investigate the effect of the quantum confinement on the threshold voltage fluctuations.

The developed 'atomistic' simulation techniques have been applied to study various fluctuation resistant MOSFET architectures including epitaxial and delta doped devices.

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